

Light Collection in Noble Liquid Detectors

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Outline

- Introduction to noble liquid scintillation
- Liquid xenon
- Liquid argon
- Liquid neon
- Liquid helium

The Noble Liquid Revolution

Noble liquids are relatively inexpensive, easy to obtain, and dense.

Easily purified

- low reactivity
- impurities freeze out
- low surface binding
- purification easiest for lighter noble liquids

Ionization electrons may be drifted through the heavier noble liquids

Very high scintillation yields

- noble liquids do not absorb their own scintillation
- 30,000 to 40,000 photons/MeV
- modest quenching factors for nuclear recoils

Easy construction of large, homogeneous detectors

Liquified Noble Gases: Basic Properties

Dense and homogeneous

Do not attach electrons, heavier noble gases give high electron mobility

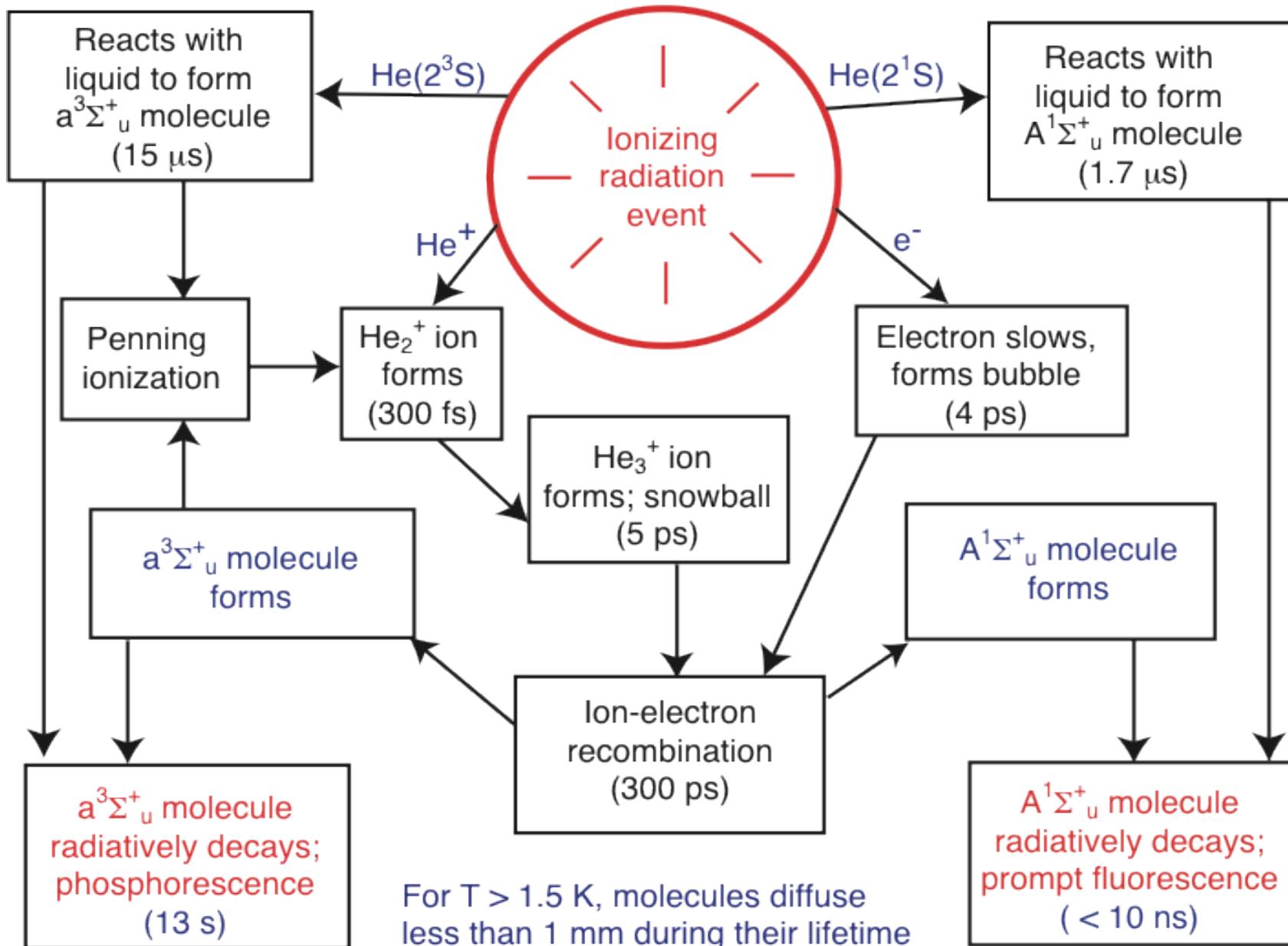
Easy to purify (especially lighter noble gases)

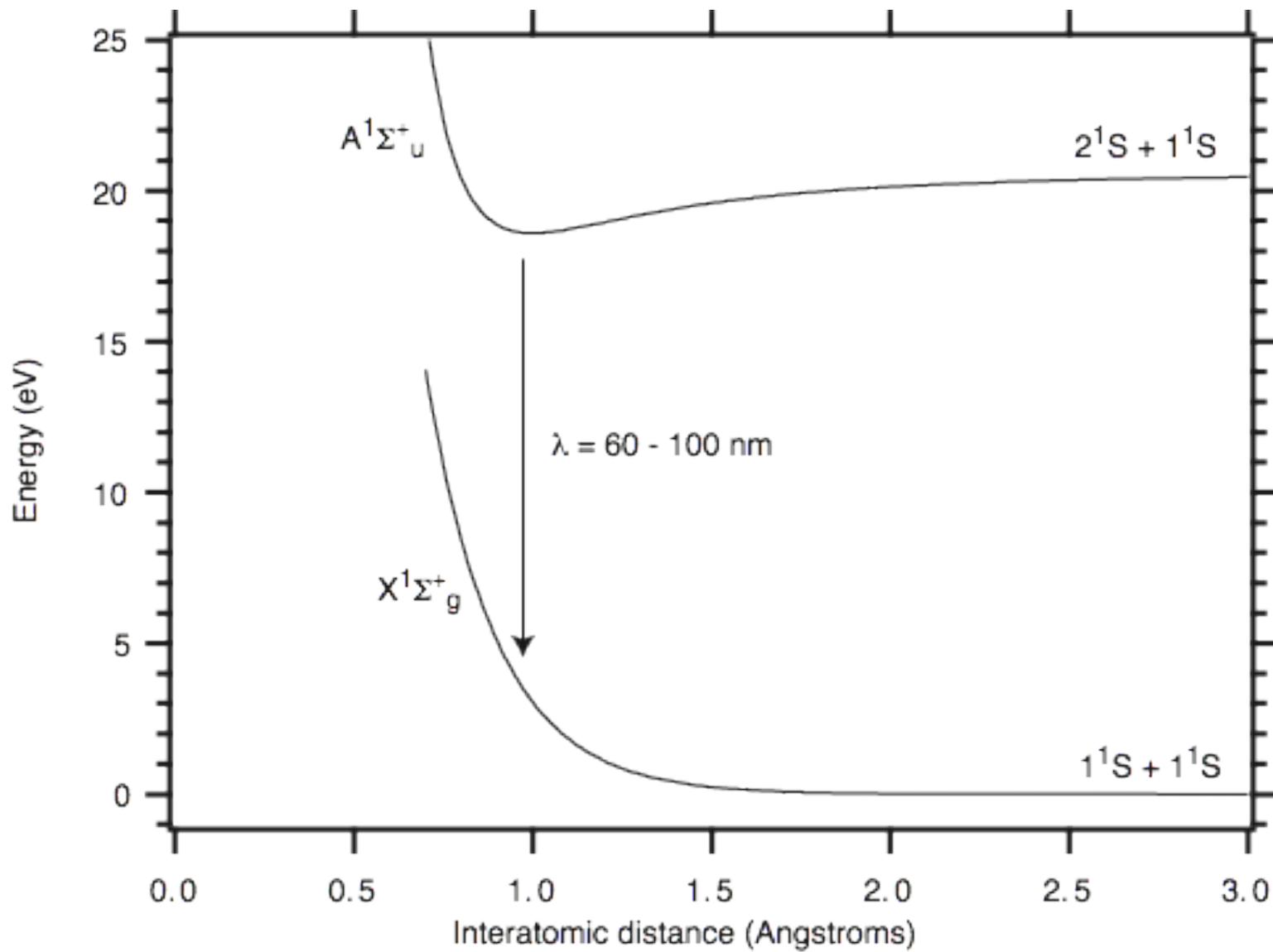
Inert, not flammable, very good dielectrics

Bright scintillators

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm ² /Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	³⁹ Ar, ⁴² Ar	1.6
LKr	2.4	120	1200	150	25,000	⁸¹ Kr, ⁸⁵ Kr	0.09
LXe	3.0	165	2200	175	42,000	¹³⁶ Xe	0.03

Liquid helium scintillation physics





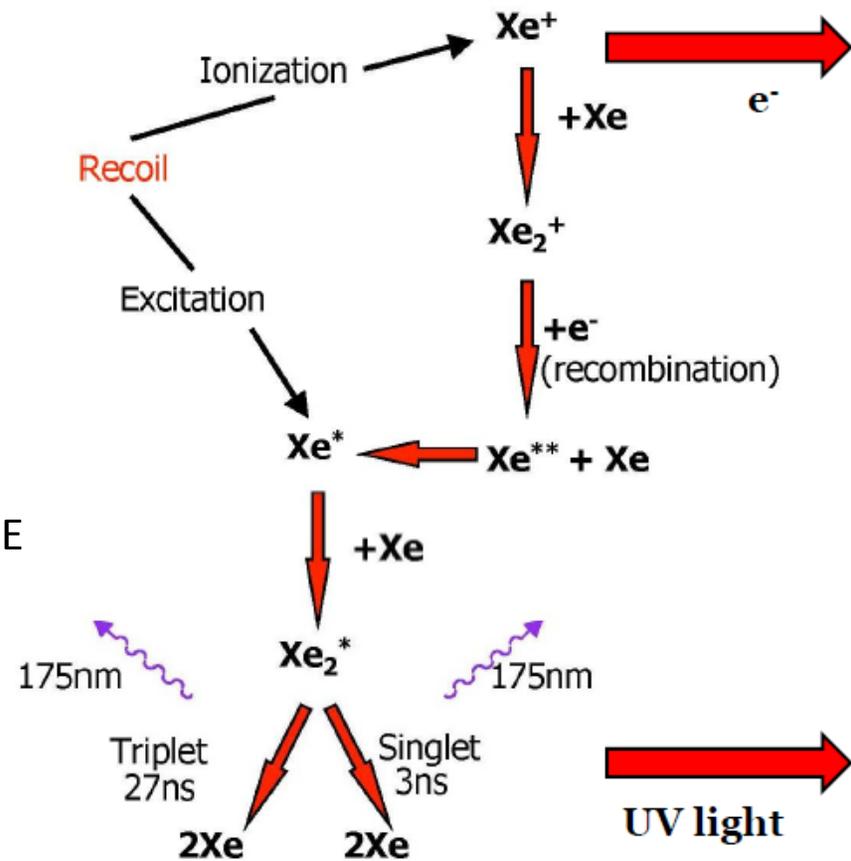
Liquid Xenon

- Inert
- High density (3g/cm^3 for liquid)
- High A^2 increases spin-independent WIMP cross-section
- Some isotopes sensitive to spin-dependent WIMP interactions
- Bright scintillator with fast ($\sim\text{ns}$) response
- High electron mobility
- Long ionization drift lengths (several meters) demonstrated
- No long-lived radioactive isotopes (other than Xe-136, with $\tau_{1/2} = 2.1\text{e}21$ years. Potential background for pp neutrinos, dark matter)
- Low cost ($\sim\$1000/\text{kg}$) and readily available in large quantities
- Easy to scale

Liquid Xenon Scintillation and Ionization

- Recoiling particle produces both atomic excitations and ionization
- Atomic excitations react with surrounding liquid to form excimers, which fluoresce
- Recombining charge also produces excimers, which fluoresce
- Non-recombining charge can be detected with proportional scintillation or wires
- Note that the Excitation/Ionization ratio depends on the recoiling particle, for low E

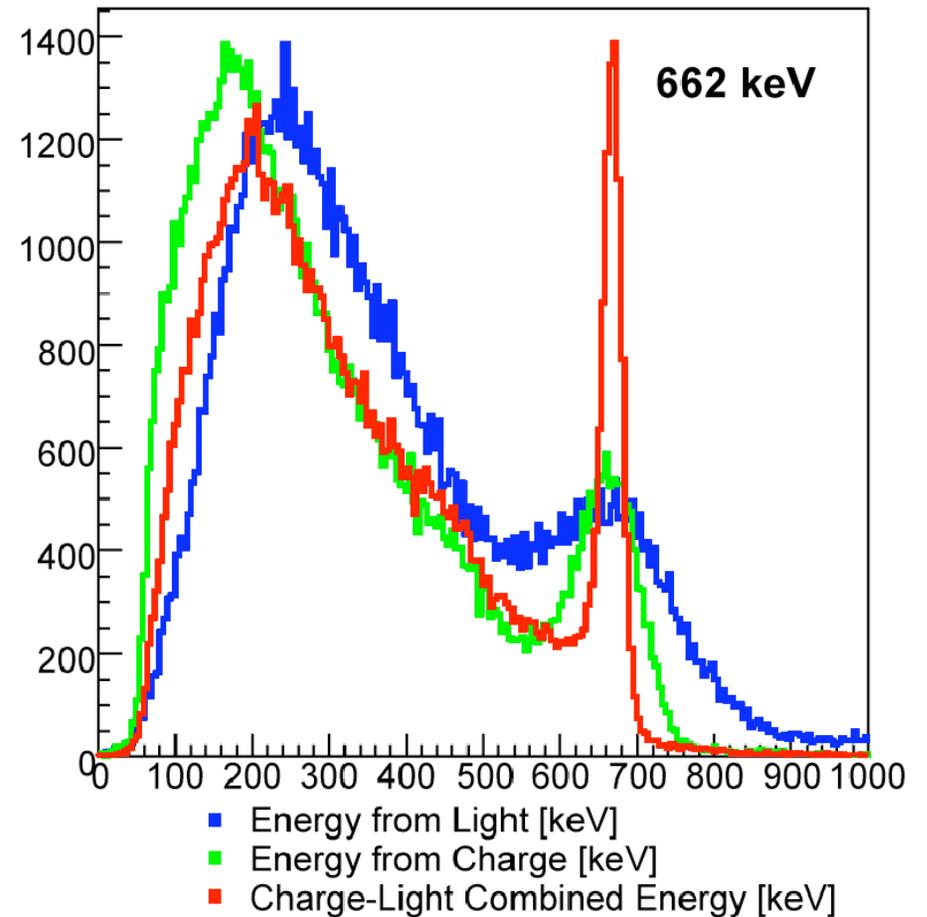
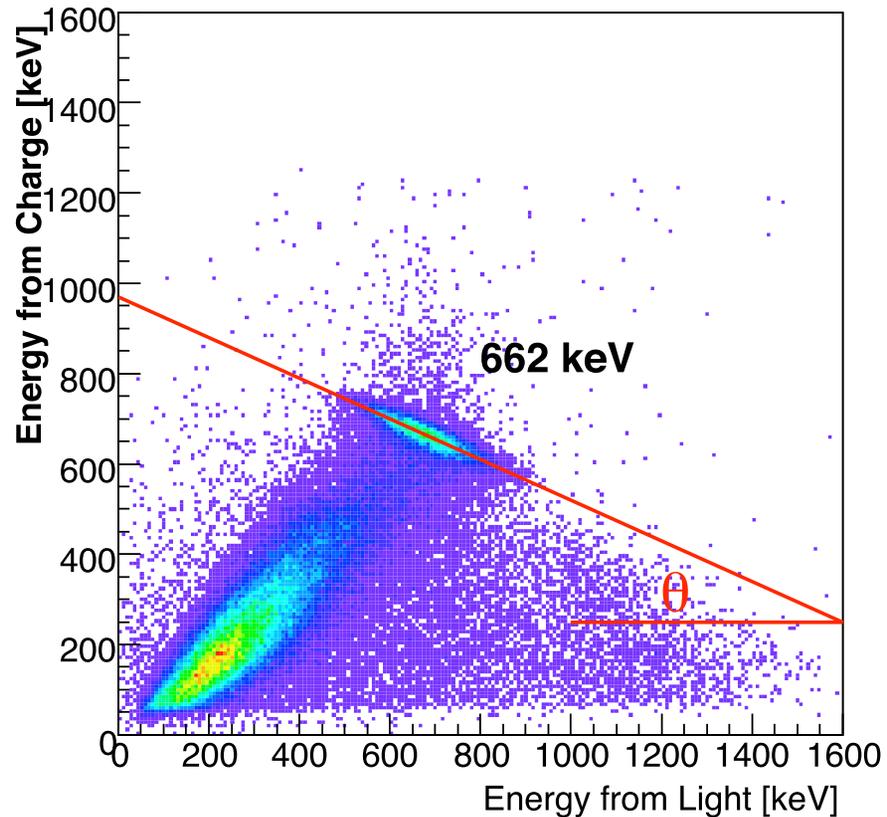
See M. Szydalis talk from this morning



Energy resolution in liquid Xe

Charge and light are anti-correlated. Combine the two signals to get optimum energy resolution!

Measured: 1.7% 1-sigma resolution at 662 keV. Projected: 1.1% with newly available PMTs.



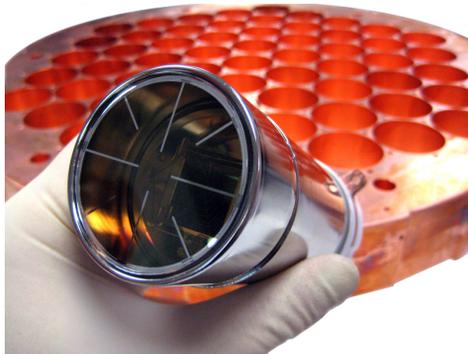
Aprile et al, Phys. Rev. B 76, 014115 (2007)

Light Collection in Liquid Xenon

A key development: cryogenic PMTs with fused silica windows

- PMT window passes 178 nm light
- No need for wavelength shifter
- 28-35% quantum efficiency
- See A Lyaskenko talk from this morning

R8778 (5 cm round)



(5 cm hexagonal)



R11410 (8 cm round)

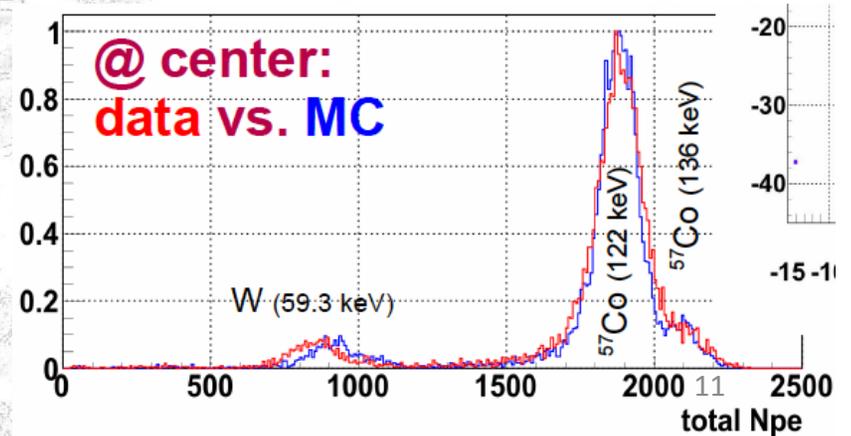
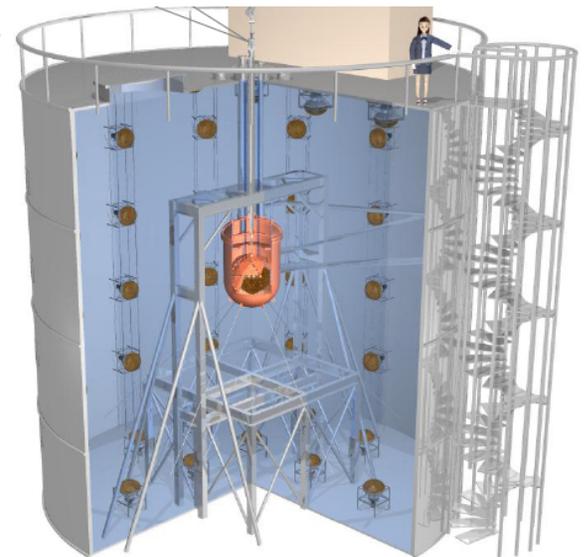
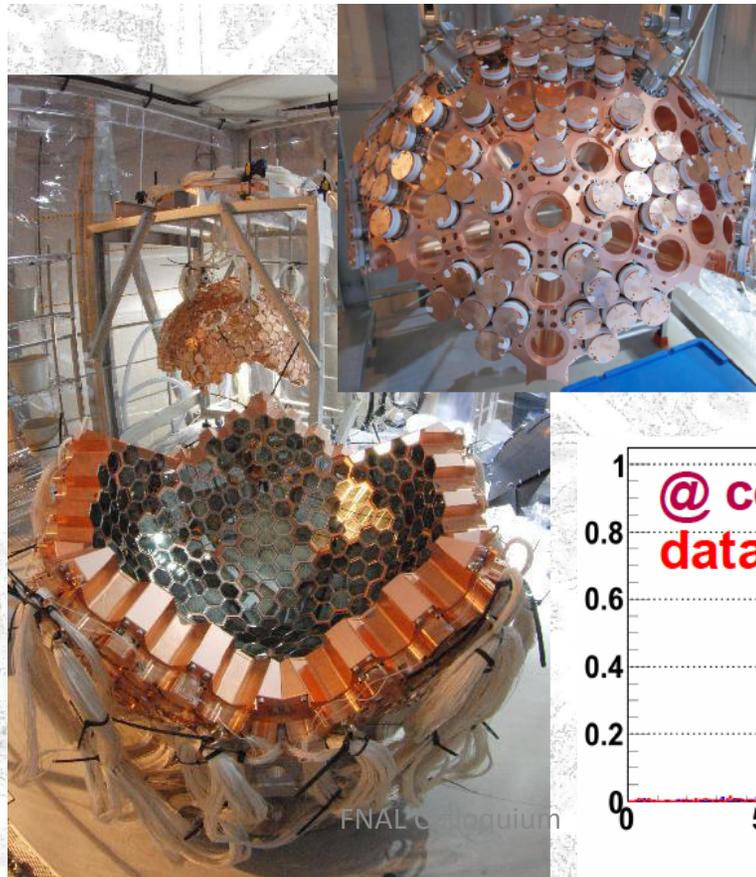
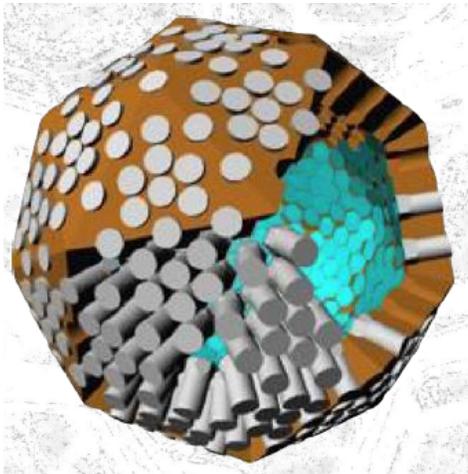


Another key development: Teflon (PTFE) is found to be extremely reflective ($> 95\%$) to LXe scintillation

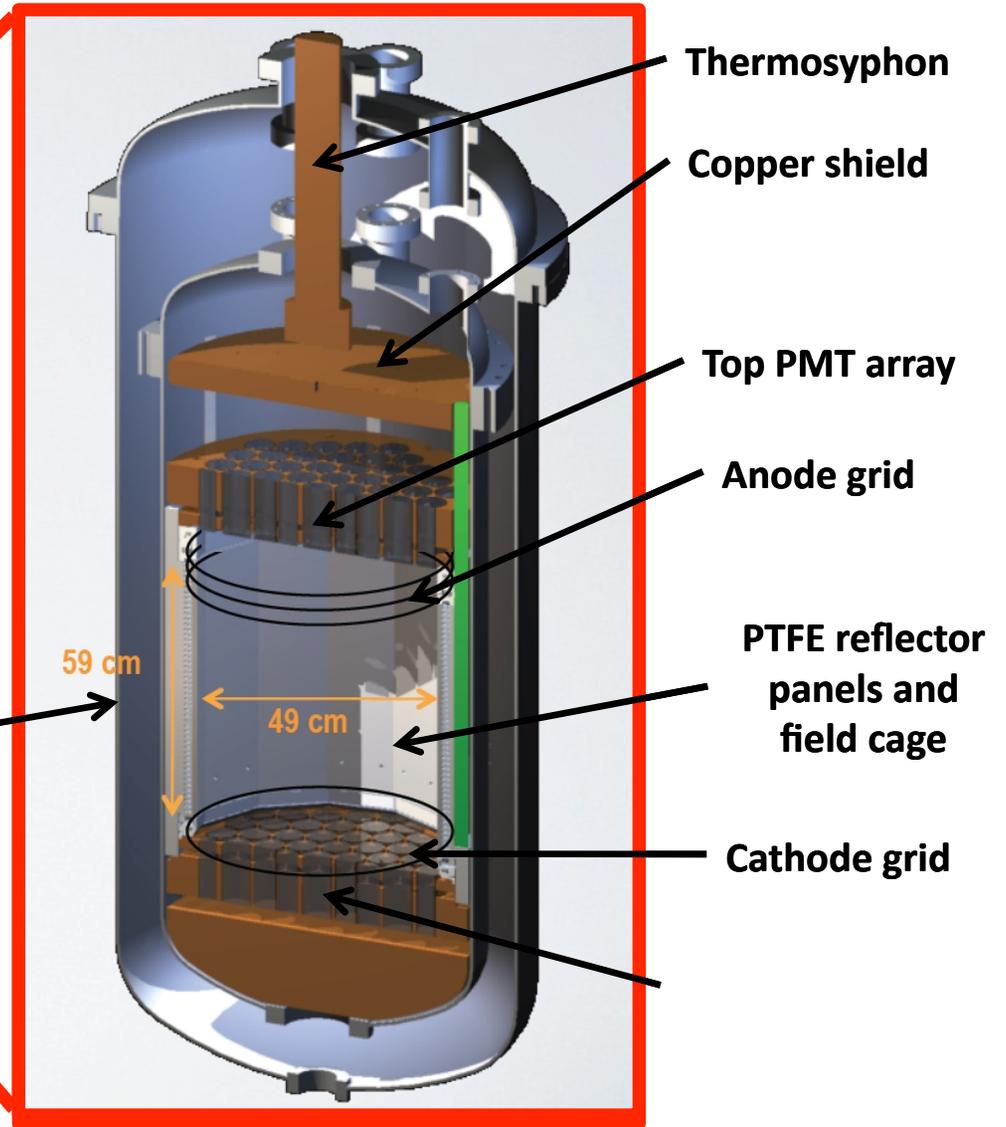
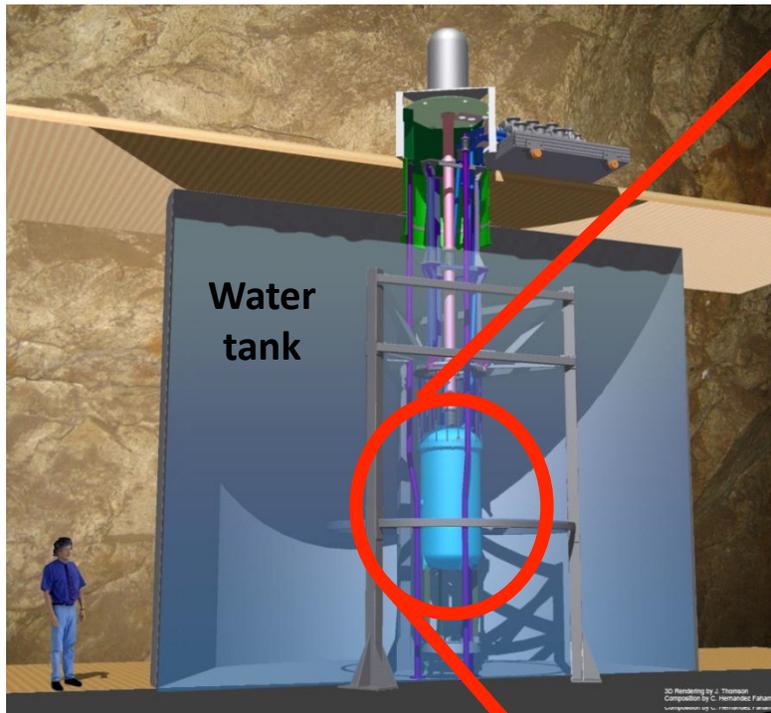
- Reflectivity in gaseous Xe is much lower $\sim 50\%$, so this is mysterious
- Internal reflection at PTFE-LXe interface?
- Allows efficient light collection in two-phase Xe, without floating PMTs at high voltage

XMASS

- A tour de force of LXe light collection
- 800 kg LXe, single phase
- Hexagonal, low-background PMTs
- Exceptional light collection: $14.9 \text{ photoelectrons/keV}_{ee}$



LUX



- 350 kg LXe, two phase
- 350 kg xenon
100 kg fiducial
- Exceptional light collection:
8.0 photoelectrons/keV_{ee}

5/29/18

LUX is cold, filled with liquid xenon, and operational, a mile underground in South Dakota



$$E_{\text{nr}} = \frac{S_1}{L_y \cdot \mathcal{L}_{\text{eff}}} \cdot \frac{S_e}{S_n}$$

Factors affecting \mathcal{L}_{eff} (all of which are likely energy-dependent!)

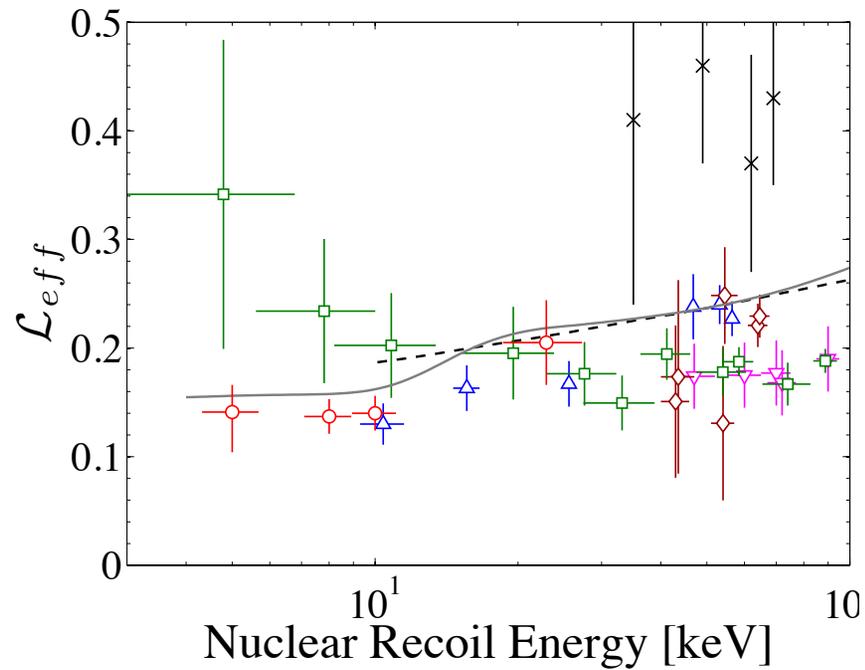
- Lindhard effect (kinematically suppressed nuclear recoil – electron excitations at low energy). Difficult to calculate at low energies.
- Ion-electron recombination efficiency. Becomes more electron-like at low energies?
- Atomic excitation, both singlet and triplet. Atomic excitation more significant at low energies?
- Bi-excitonic quenching a la Birk's law. Should be less significant at low energies.

For discussion of models of these effects, see:

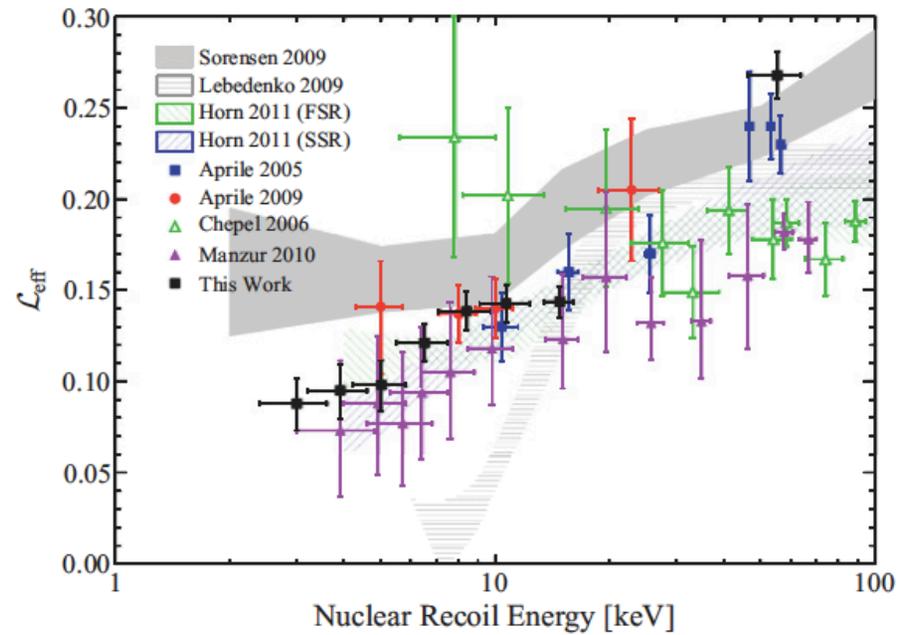
Sorensen, arXiv:1007.3549, Dahl and Sorensen arXiv:1101.6080,
Bezrukov, Kahlhoefer, and Lindner, arXiv: 1011.3990

After some controversy, \mathcal{L}_{eff} is now believed to decrease at low energy

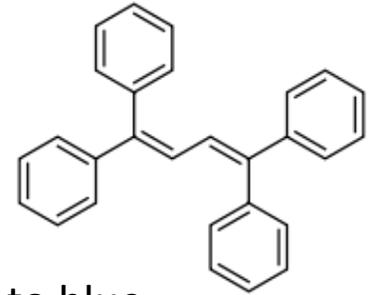
Aprile et al, 2009



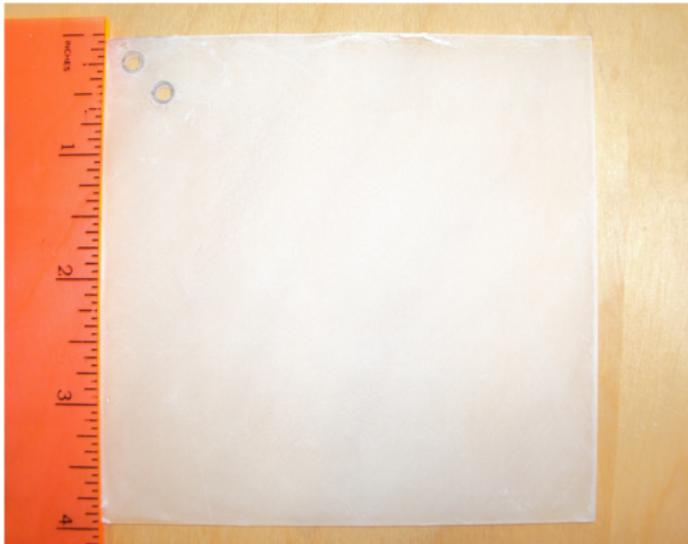
Plante et al, 2011



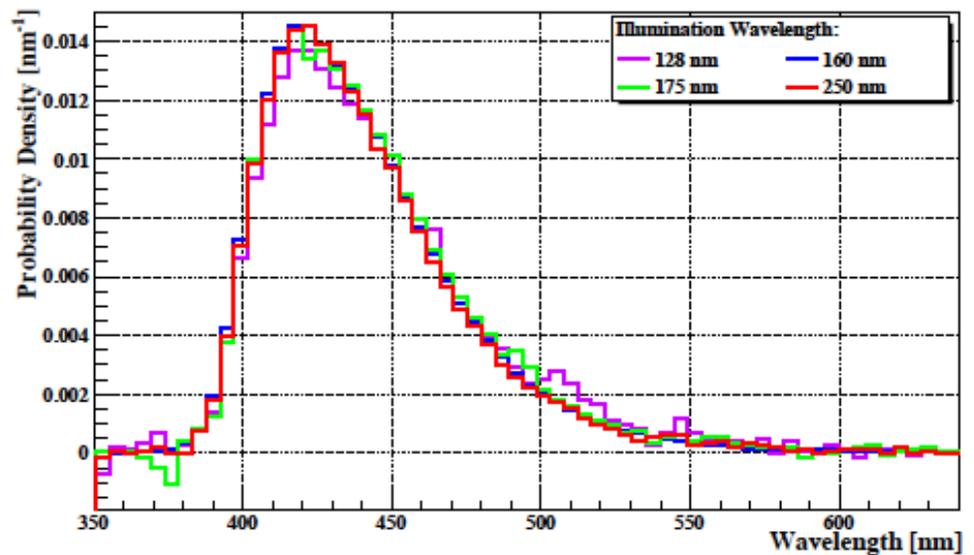
Tetraphenyl Butadiene (TPB), $C_{28}H_{22}$



Highly efficient fluor, commonly used to convert VUV scintillation light to blue
Can be evaporated or sprayed onto surfaces, or doped into plastic films (like polystyrene)
Has been used for liquid argon, liquid neon, liquid helium scintillation readout
“Frosted glass” appearance, typical thickness of 200 $\mu\text{g}/\text{cm}^2$



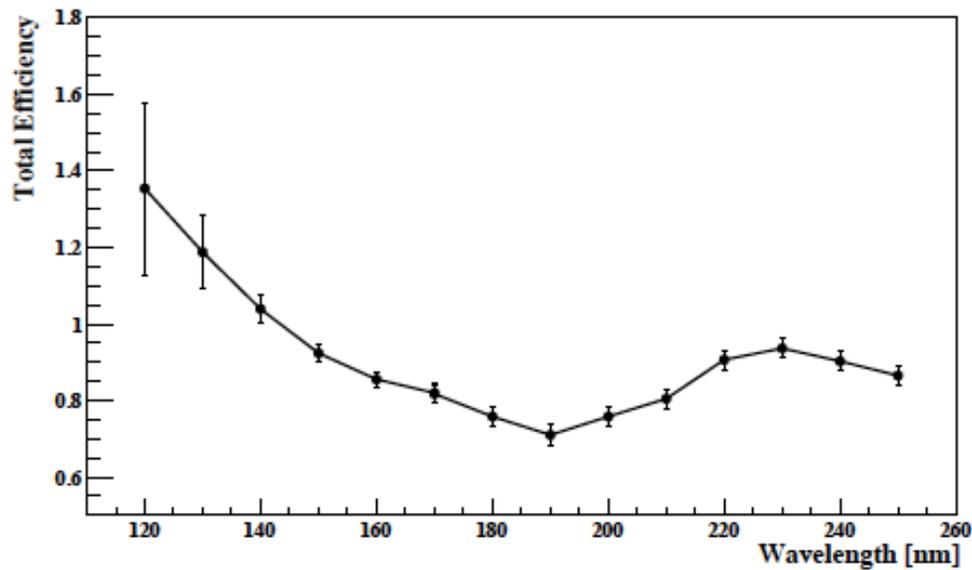
TPB emission spectrum



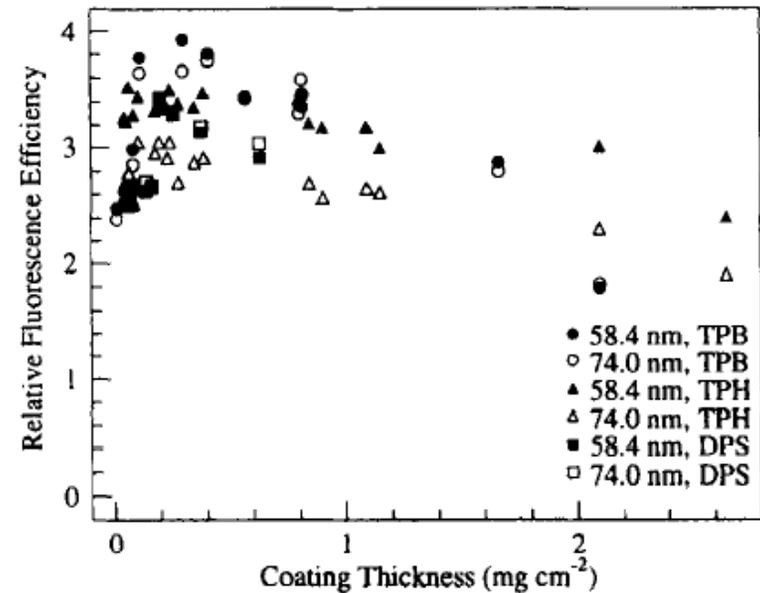
V. Gehman et al, NIM A 654, 116 (2011)

TPB Fluorescence efficiency

V. Gehman et al, NIM A 654, 116 (2011)

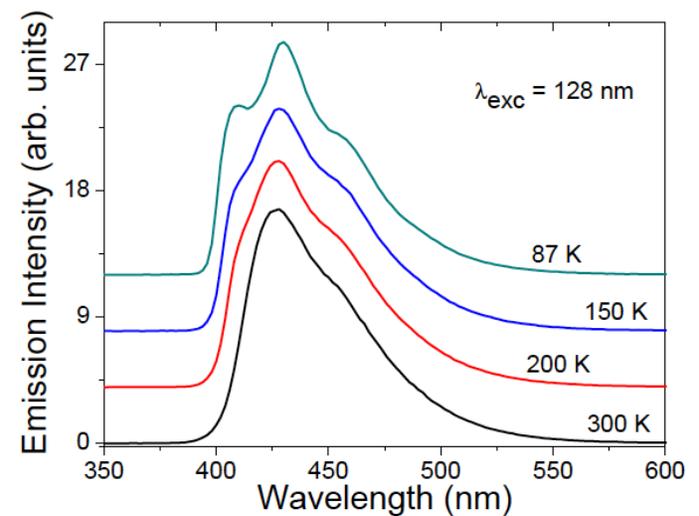
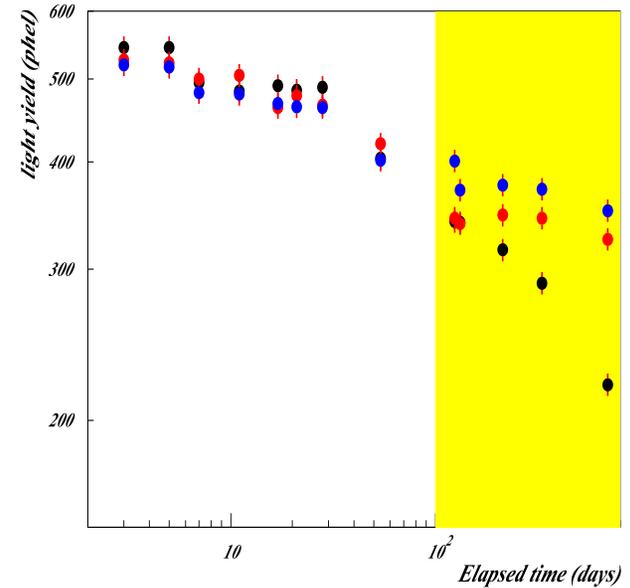


McKinsey et al, NIM A 132, 351 (1997)



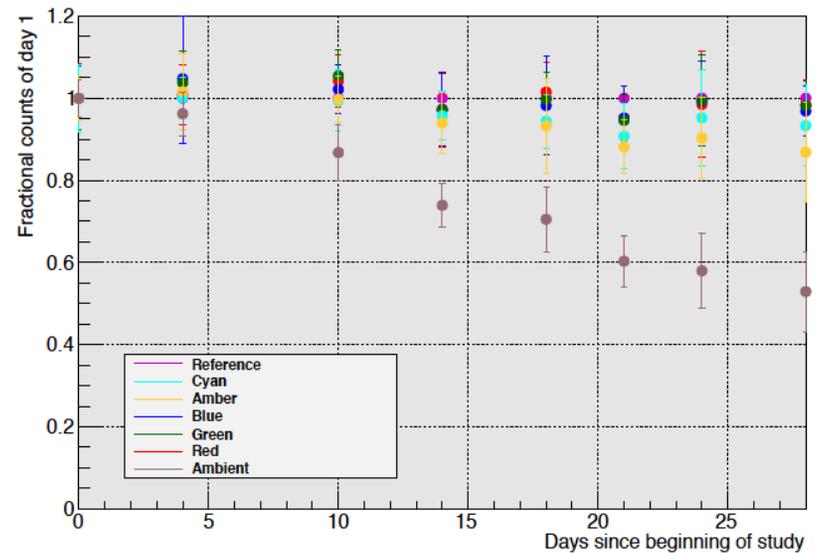
Recent TPB Developments

- Aging studies of TPB films (Segreto talk, Thursday)
- Characterization at emission at LAr temperature (Francini talk, Thursday)

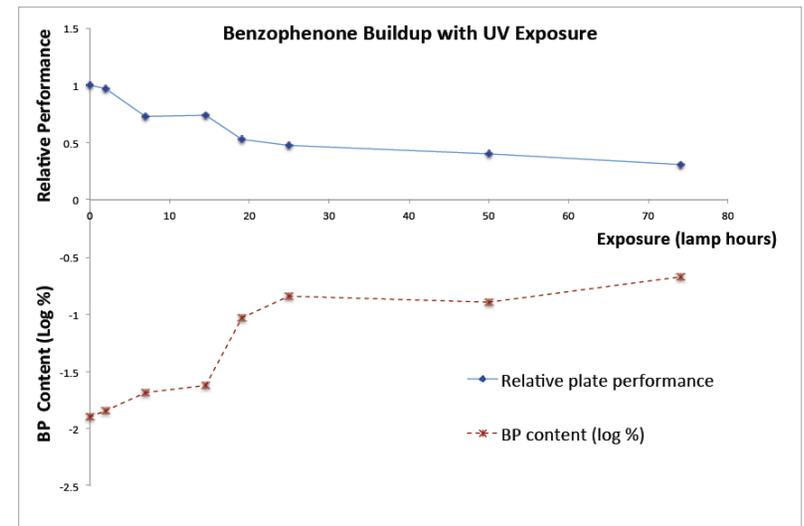


Recent TPB Developments

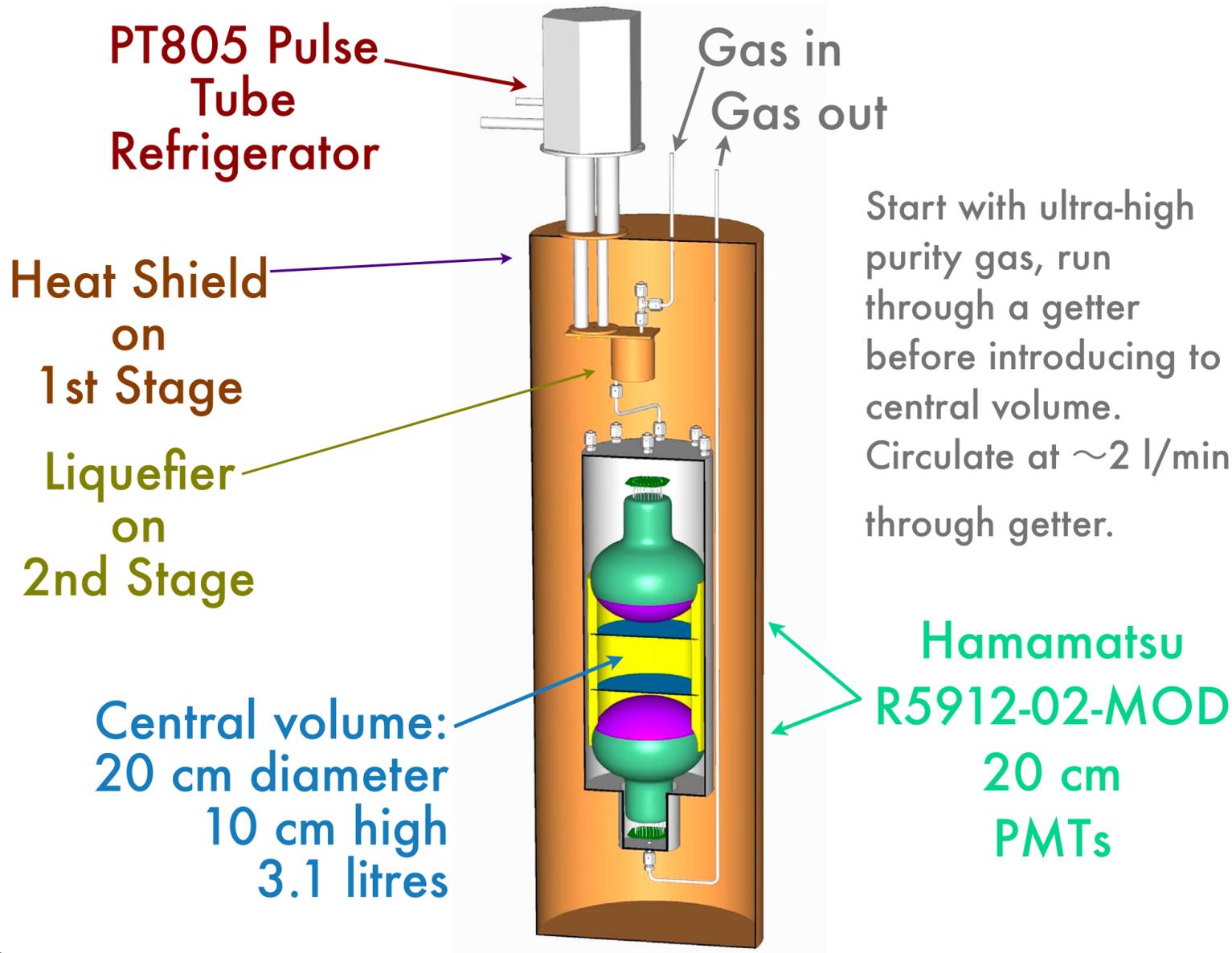
- Effects of exposure to Optical and Near-UV light (Mufson talk, Thursday)



- Studies of photodegradation mechanisms (VanGemert talk, Thursday)



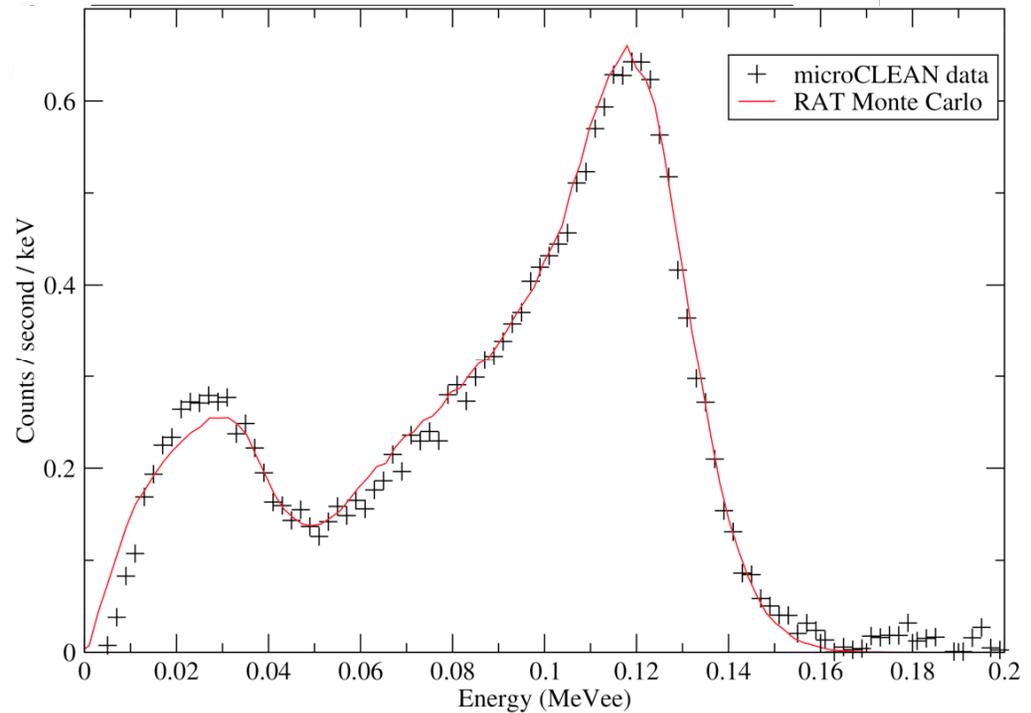
MicroCLEAN



MicroCLEAN signal yield in LAr

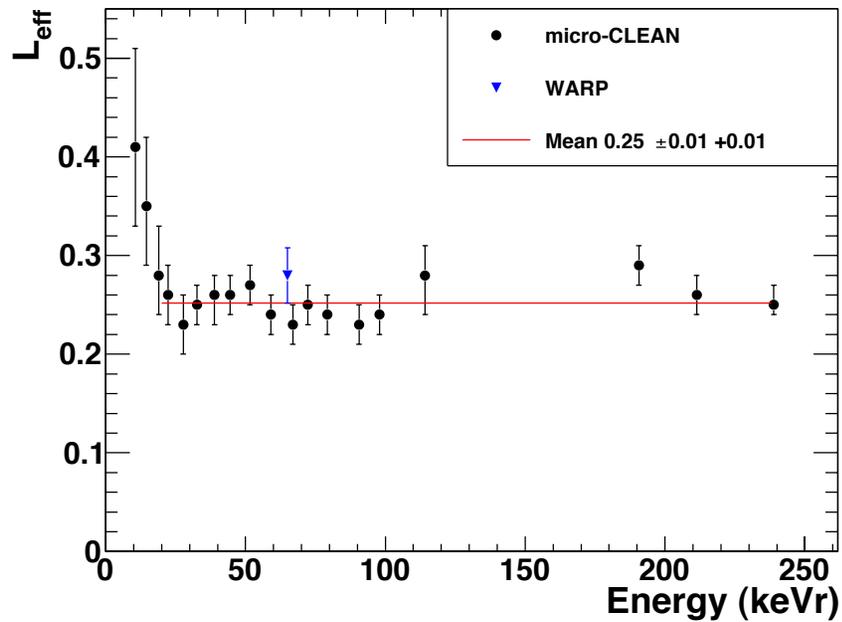
6.0 photoelectrons/keV

Lippincott et al, Phys. Rev. C 78, 035801 (2008)

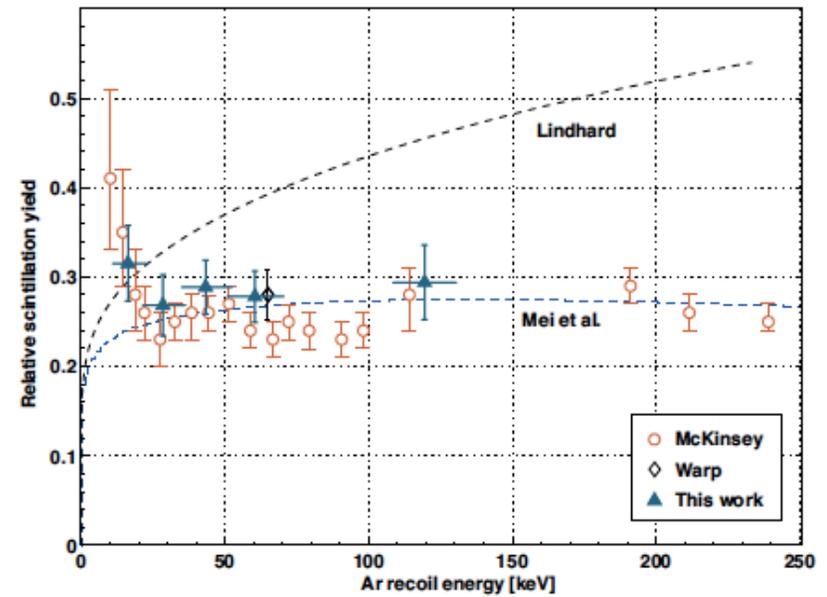


Liquid Argon Scintillation Efficiency

D. Gastler et al, Phys. Rev. C 85, 065811 (2012).

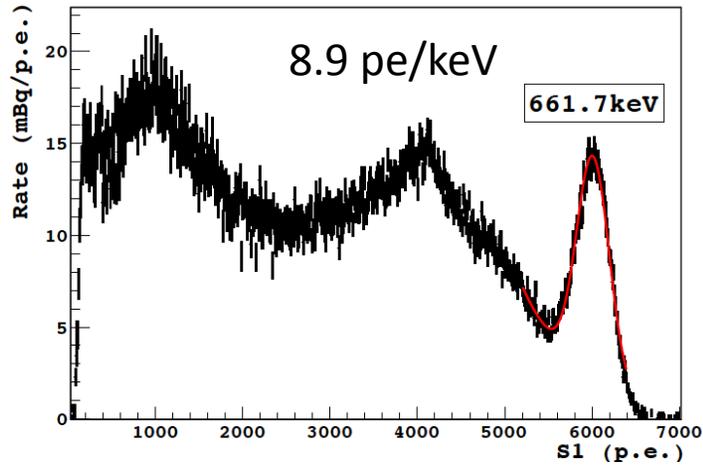


C. Regenfus et al, arXiv:1203.0849

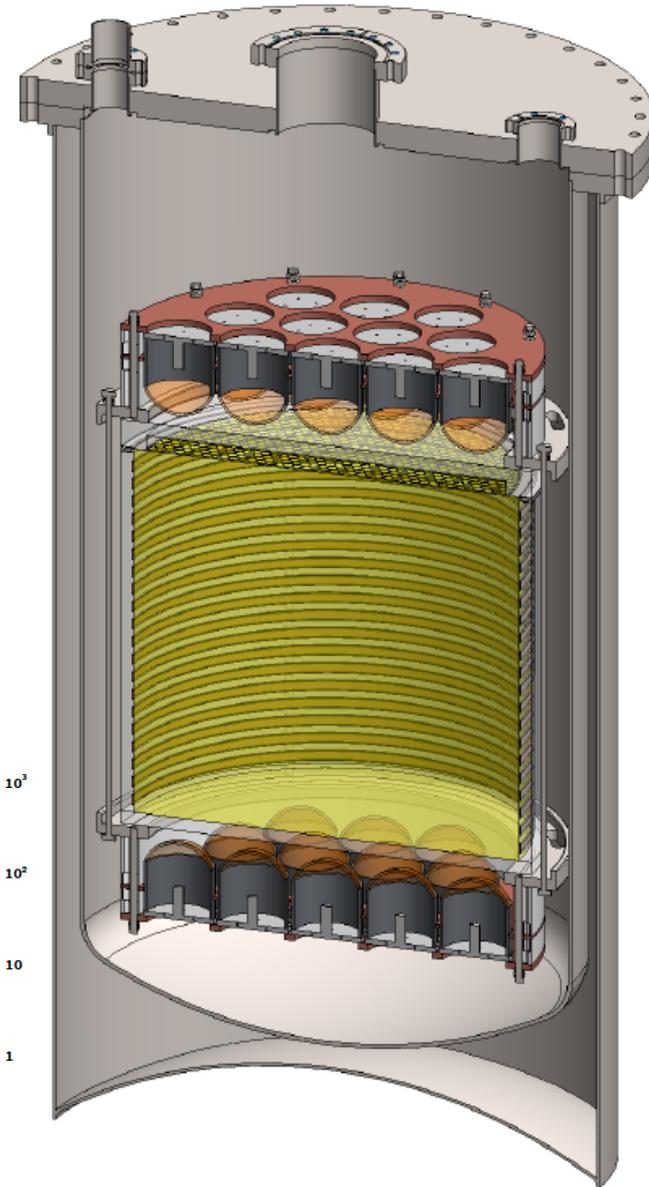


DarkSide-10 data

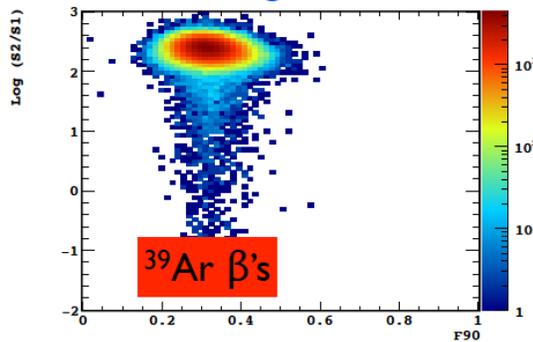
Also see talk by Emilija Pantic on Friday



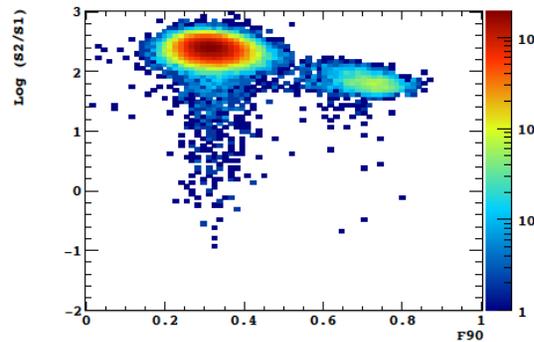
DS-50 model



Background



Am-Be Source



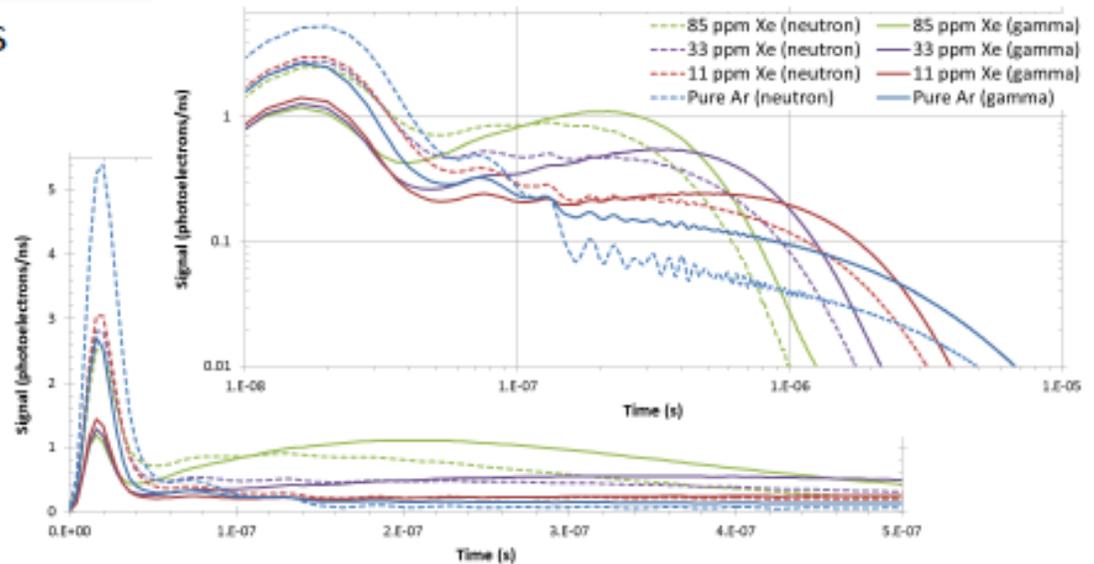
Xenon doping of LAr (preliminary)

As Xe-dopant concentration increases in the range studied:

- Light yield improves.
- Prompt fraction decreases.
- Delayed “bump” increases, arrives sooner, and decays more rapidly.

Neutrons have:

- Larger prompt fraction.
- Smaller delayed “bump”.

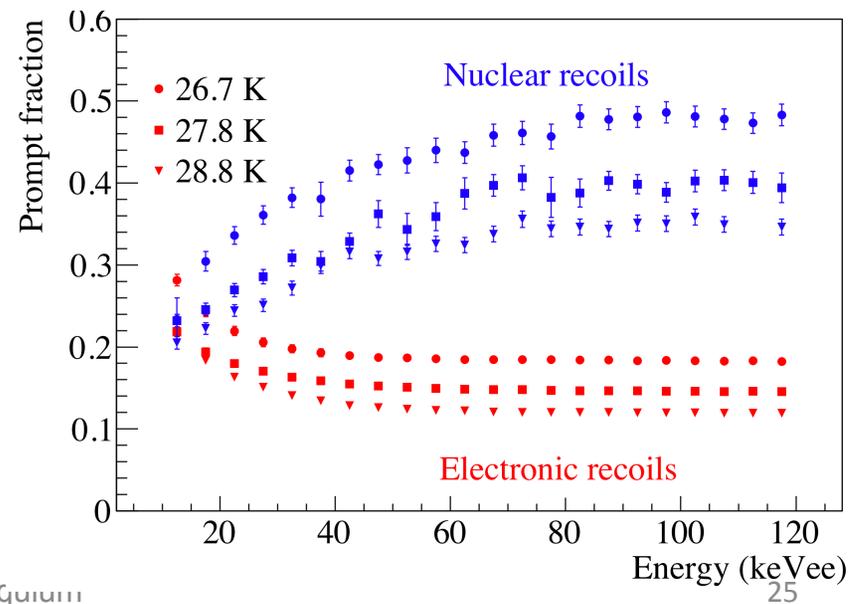
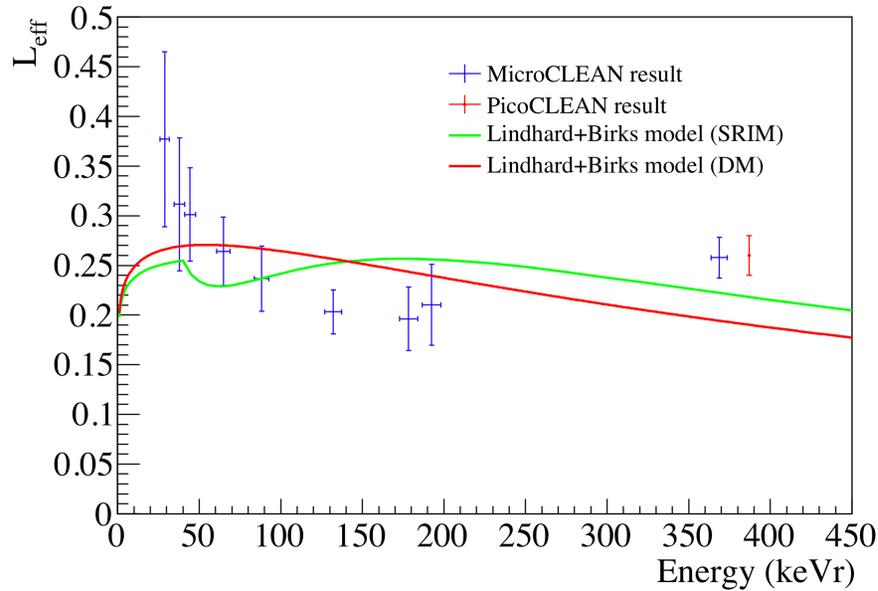
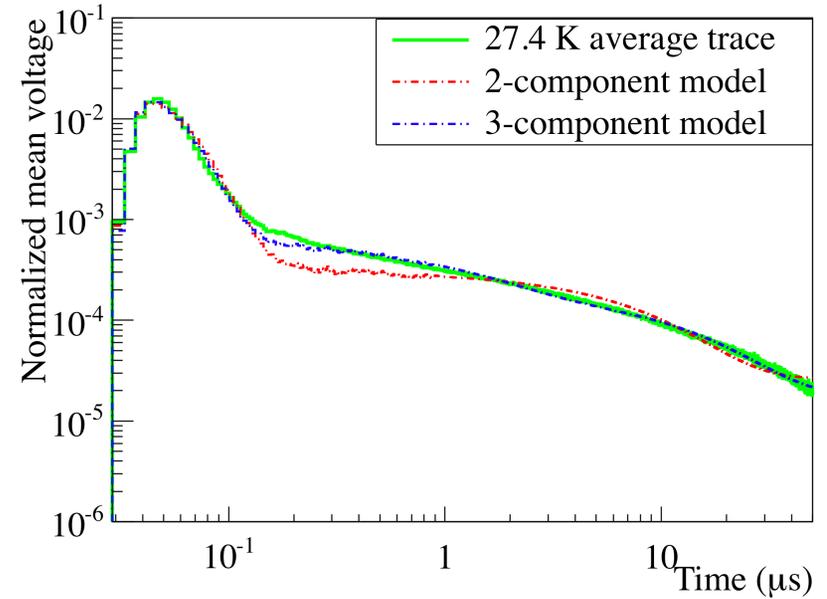
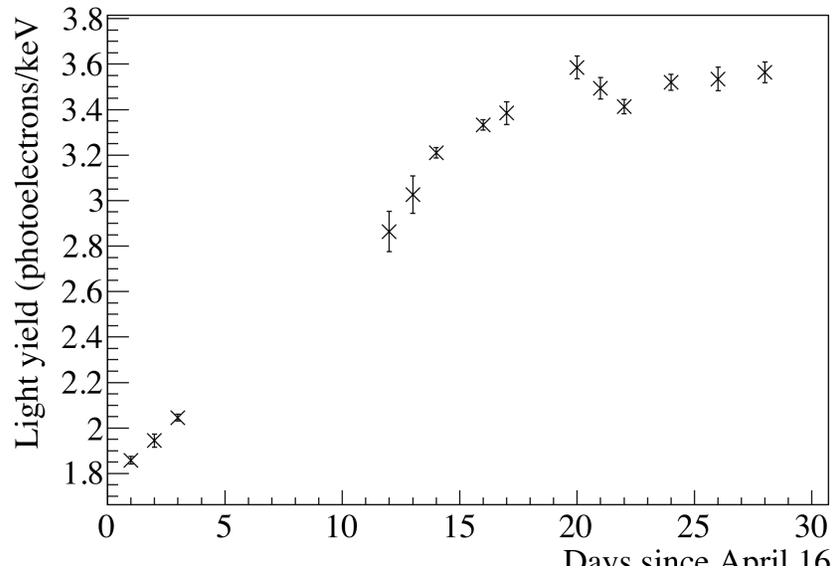


Average waveforms for $\sim 10^5$ of each type of event for different dopant concentrations in the range around the Co-57 photopeak at 122 keV.

Xenon concentration by mass (ppm) ($\pm 50\%$)	0	11	33	85
Light Yield (photoelectrons/keV) (± 0.1)	4.1	4.5	4.9	4.9
Decay constant of slow component (ns) (± 10)	1800	1070	460	200
Delay between prompt and delayed components (ns) (± 10)	N/A	640	460	310

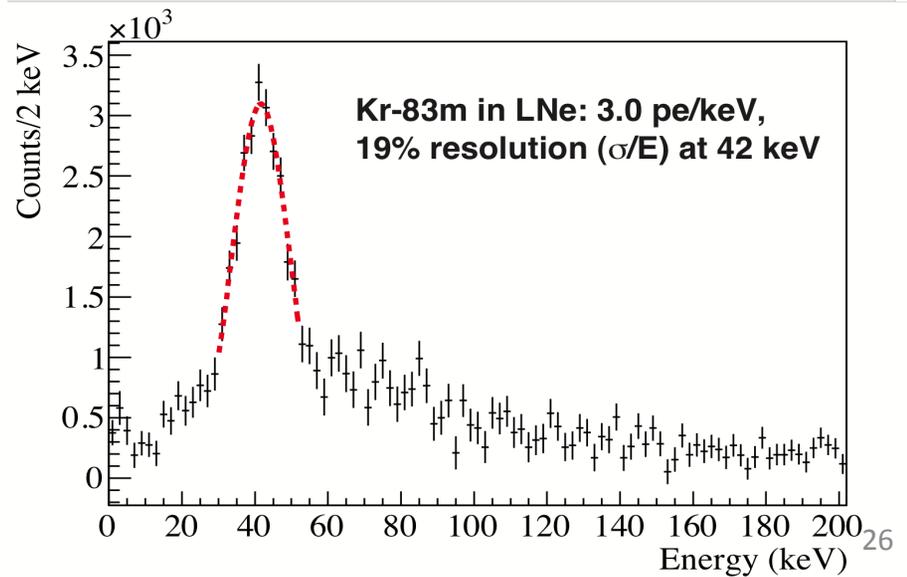
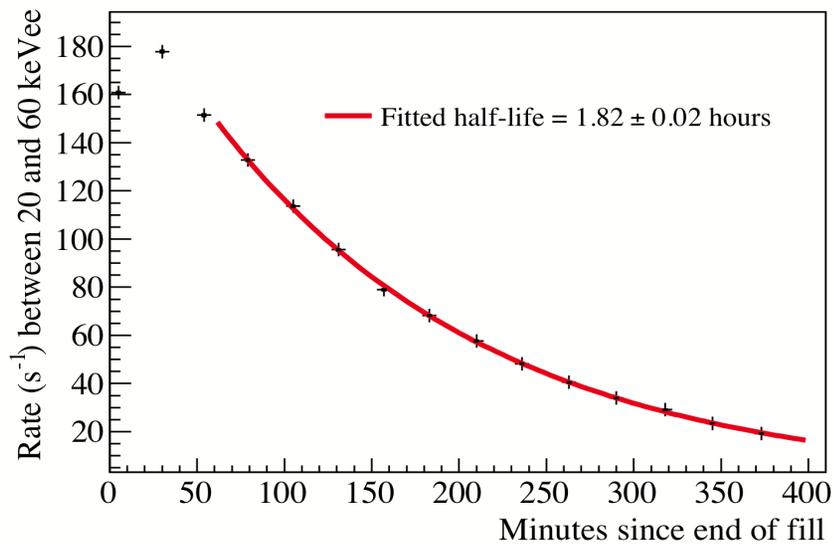
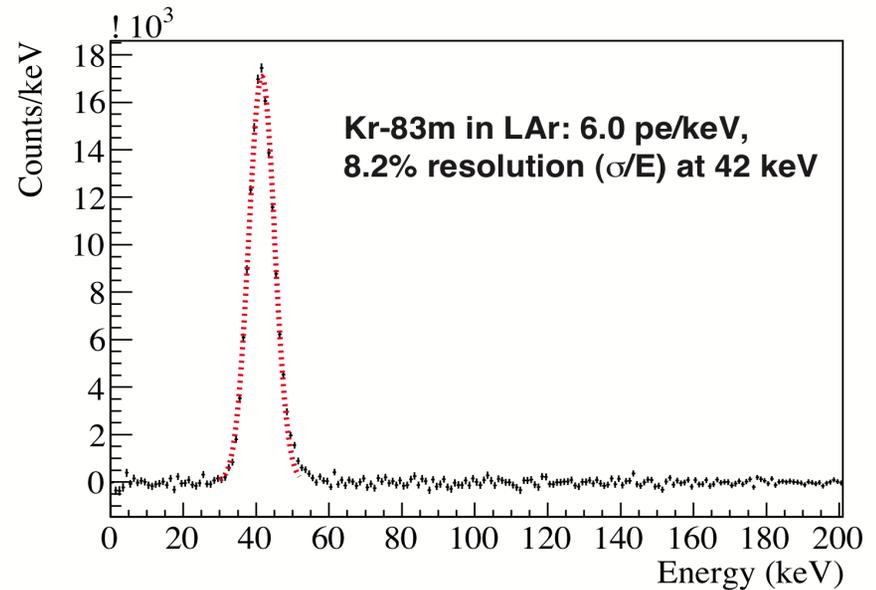
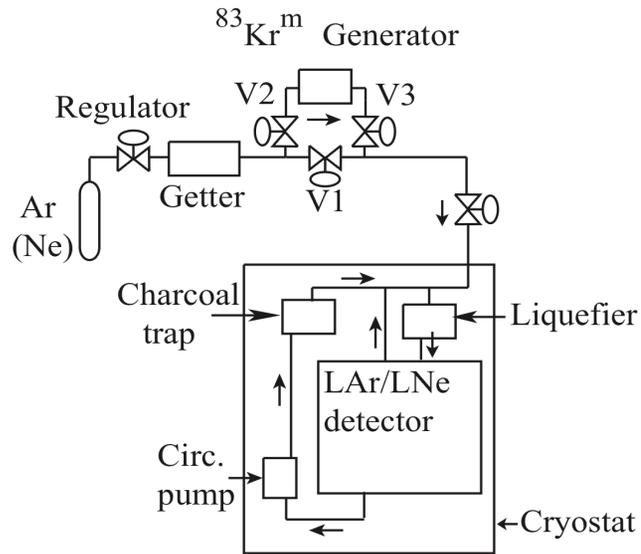
LNe in MicroCLEAN (Lippincott et al, Phys. Rev. C 86, 015807 (2012))

3 photoelectrons/keV



Kr-83m data in MicroCLEAN

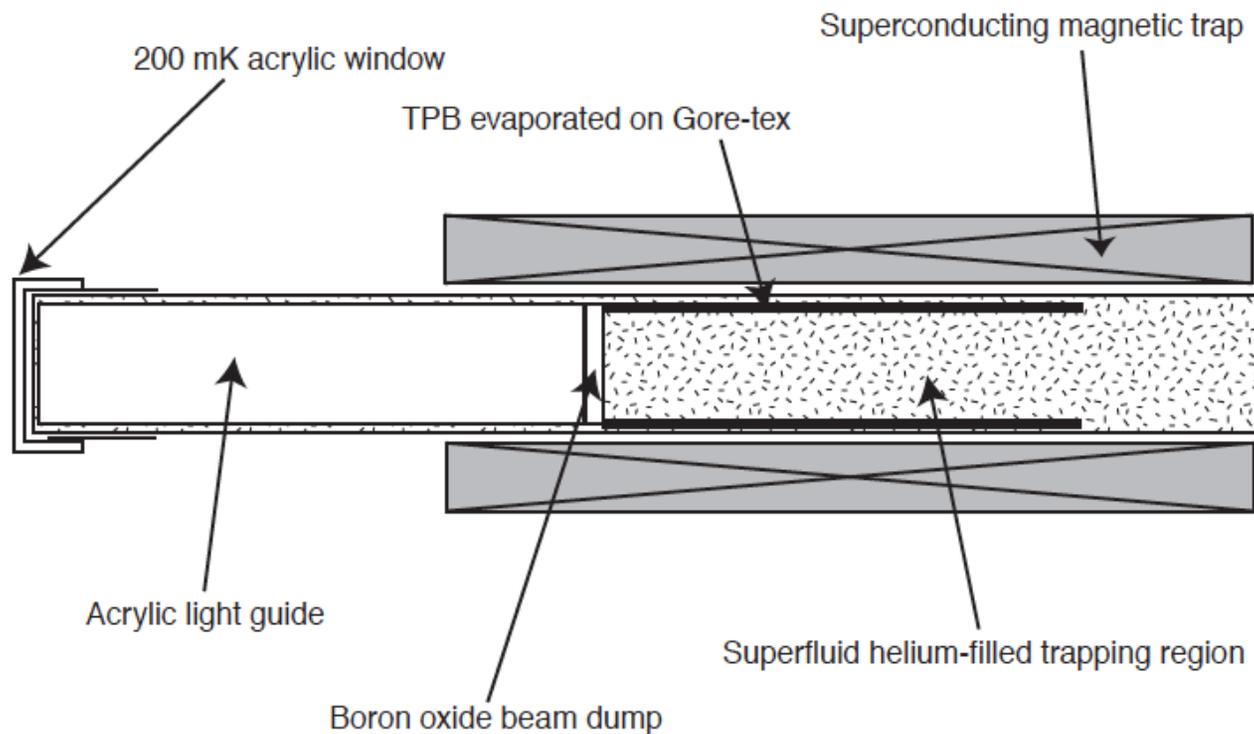
Lippincott et al, Phys. Rev. C 81, 045803 (2010).



Liquid helium

Used to create, store, and detect ultracold neutrons

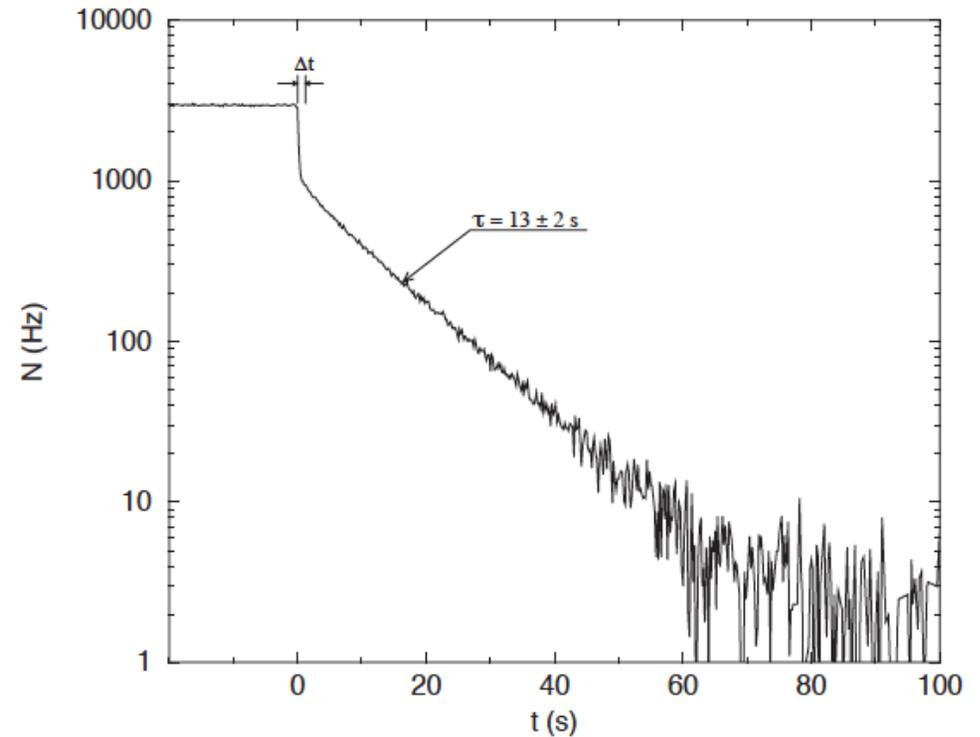
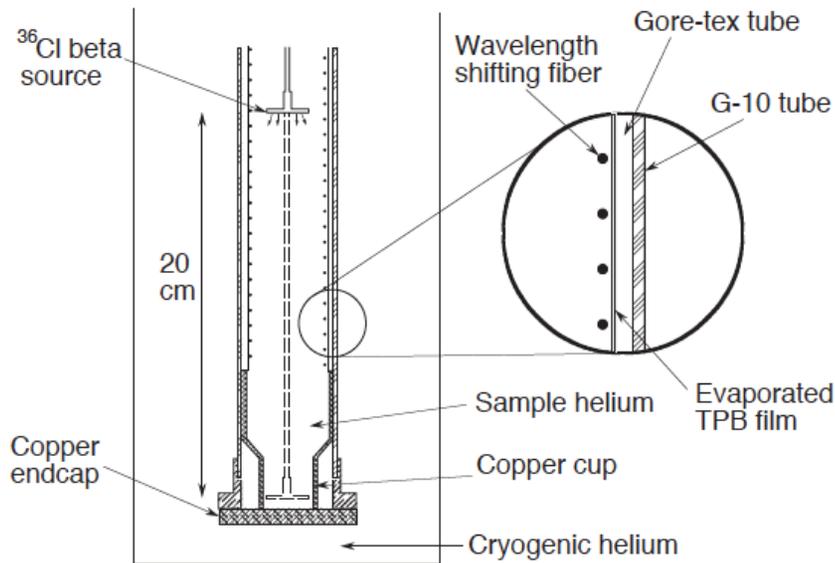
Demonstrated signal yields up to $0.1 \text{ photoelectrons/keV}_{ee}$, with unfavorable light collection



See P Huffman talk on Thursday.

Triplet helium excimer fluorescence

In liquid helium, the triplet component has an extremely long lifetime, due to small spin-orbit coupling
13 second decay constant seen by removing a radioactive source, see McKinsey et al., Phys. Rev A 59, 200 (1999)

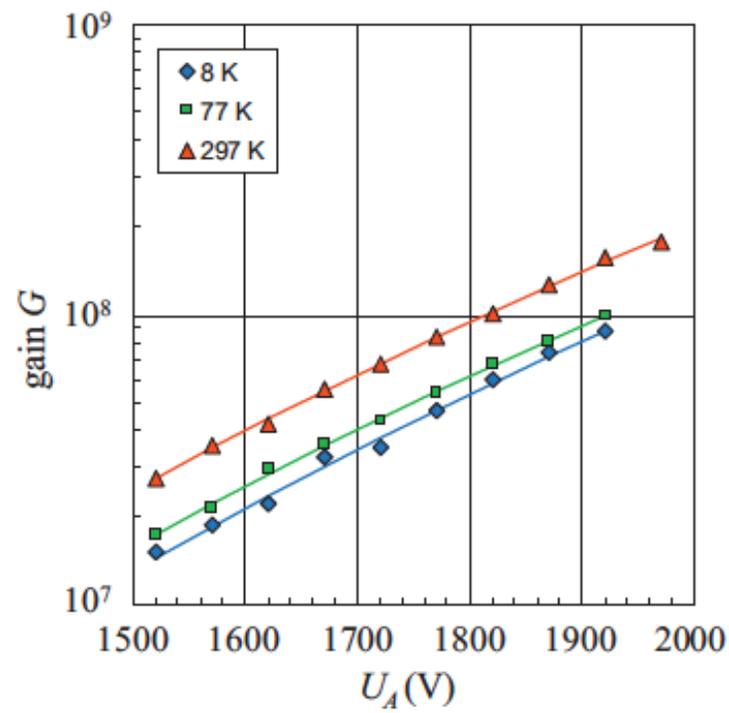
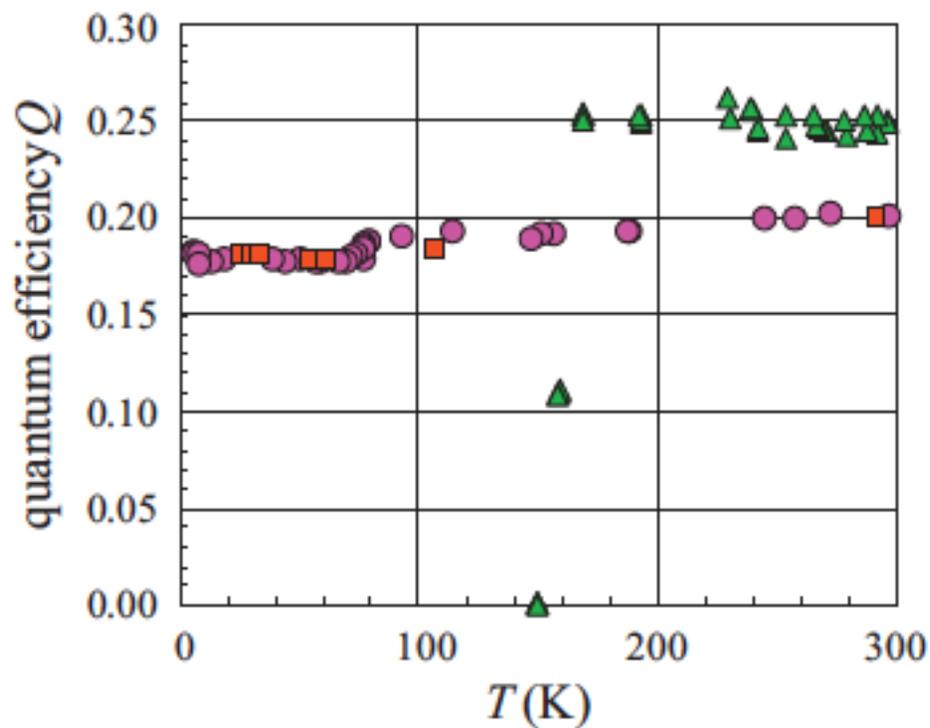


Recent advance in liquid helium light collection

PMTs mounted at 4K (H.O. Meyer, NIM A 621, 437 (2010).

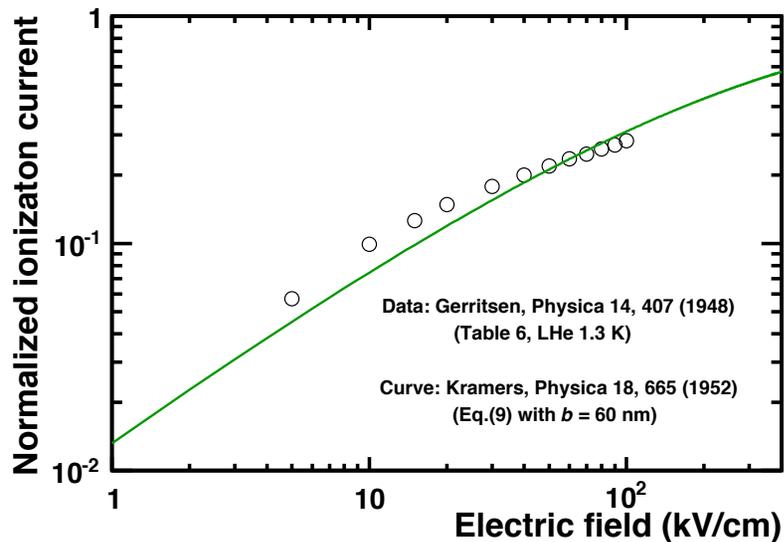
Hamamatsu model R7725-mod

Operated in cold (8 K) helium gas without additional afterpulsing

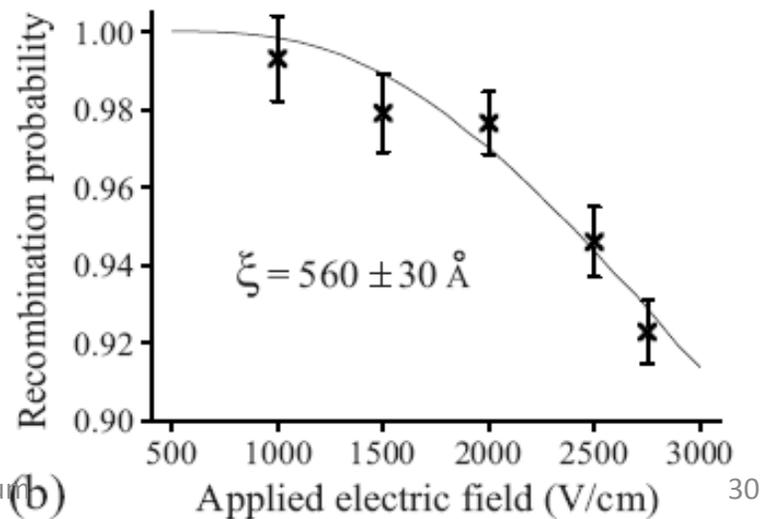
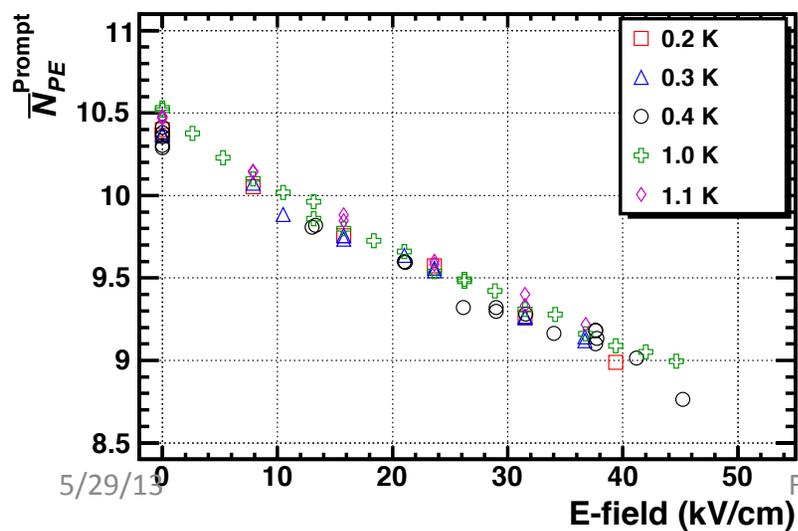
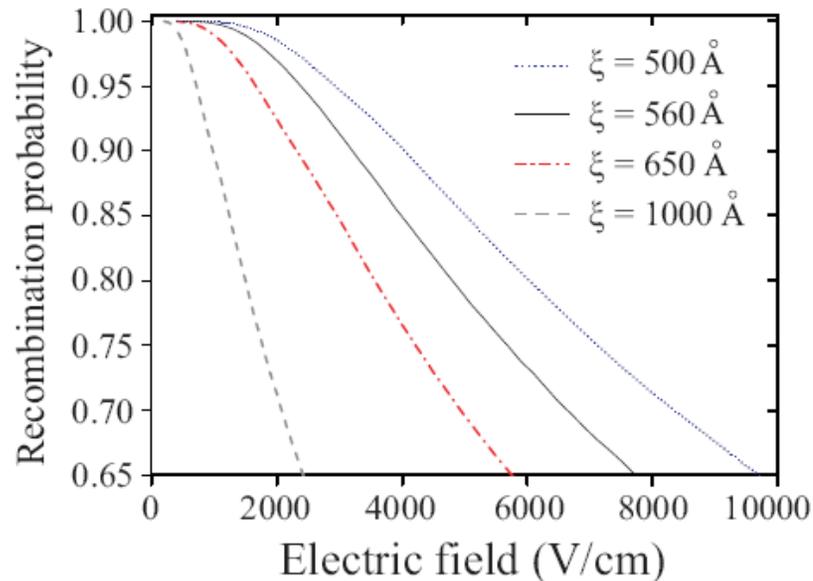


Helium scintillation vs. electric field

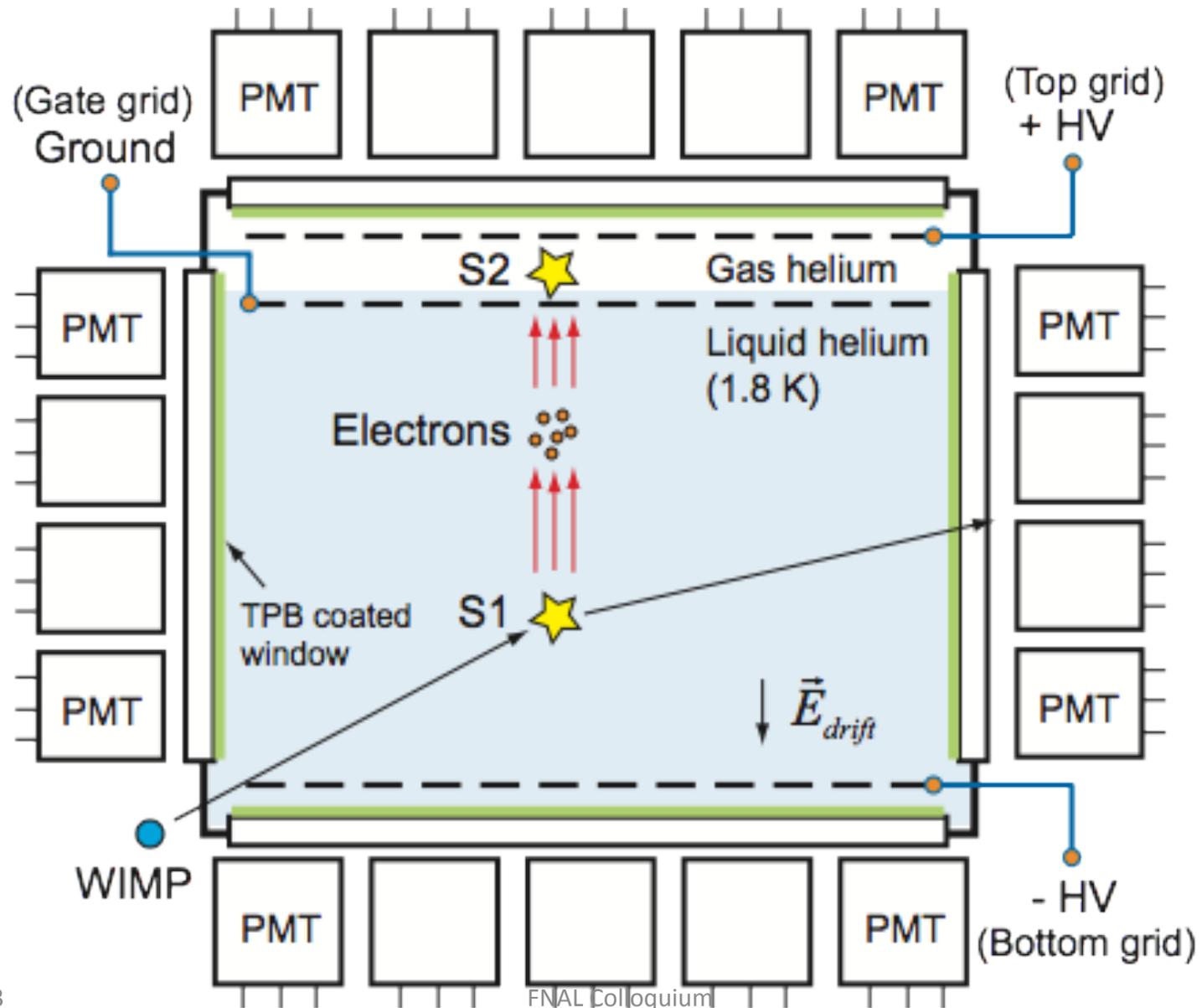
Alpha scintillation yield vs. applied field, T. Ito et al, 1110.0570

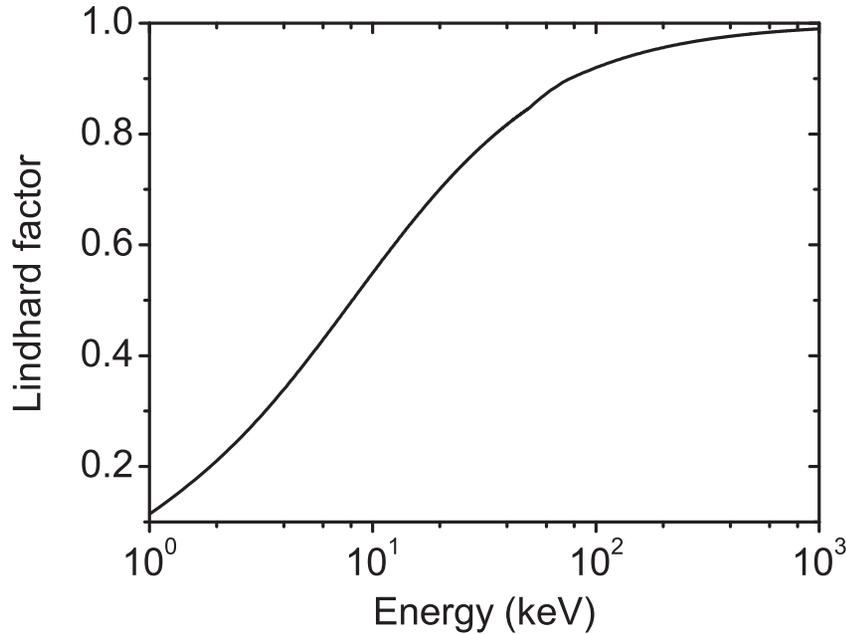


Beta scintillation field quenching: W. Guo et al, JINST 7, P01002 (2012)



Light WIMP Detector Concept

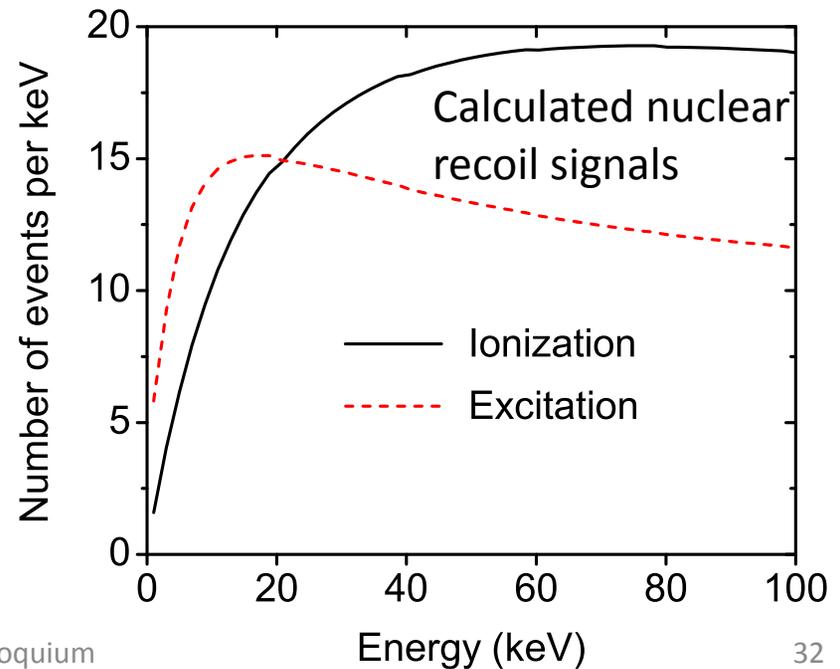
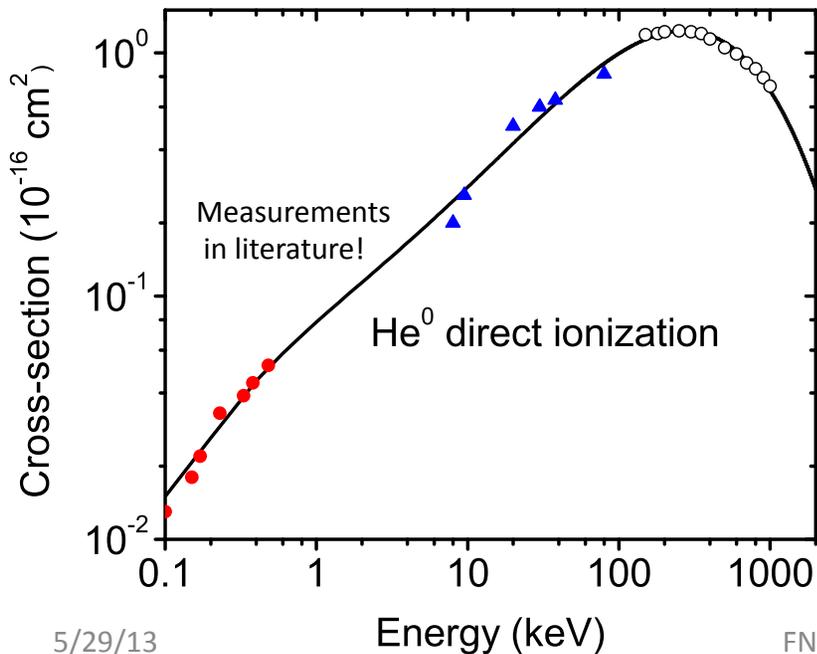




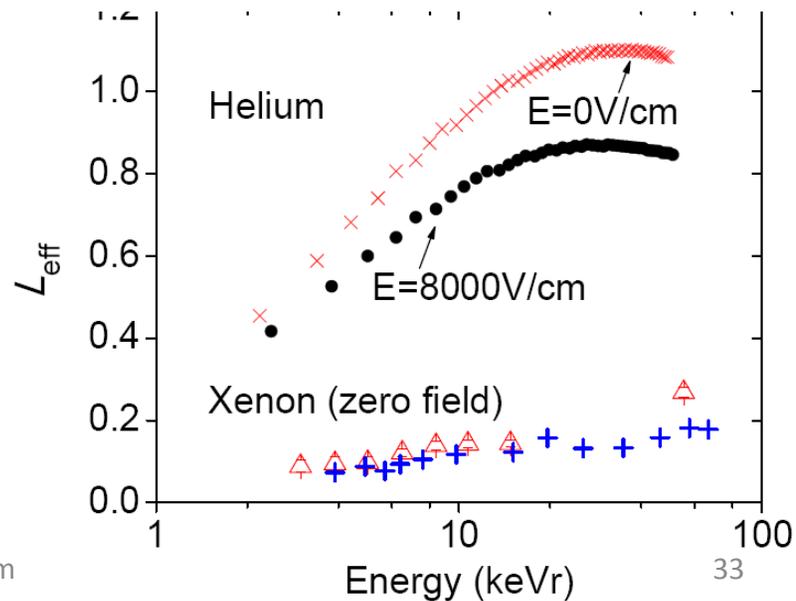
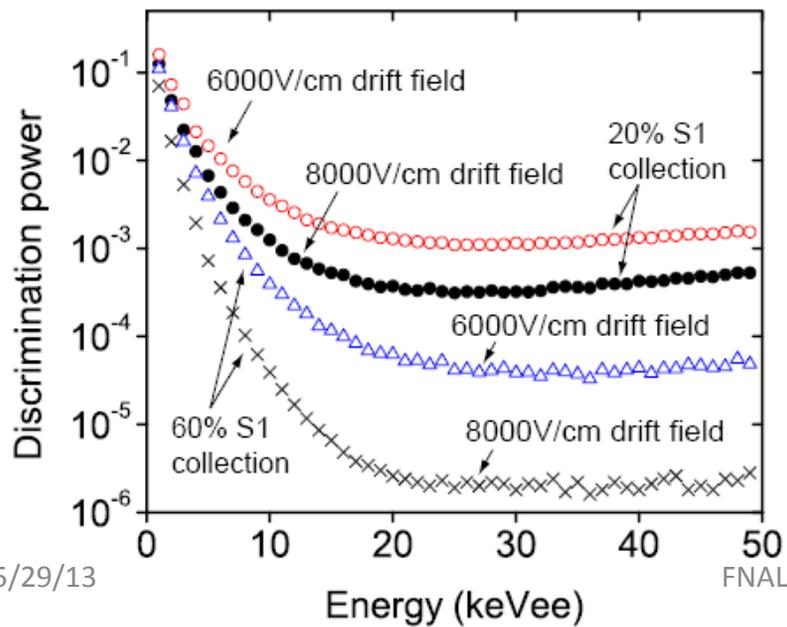
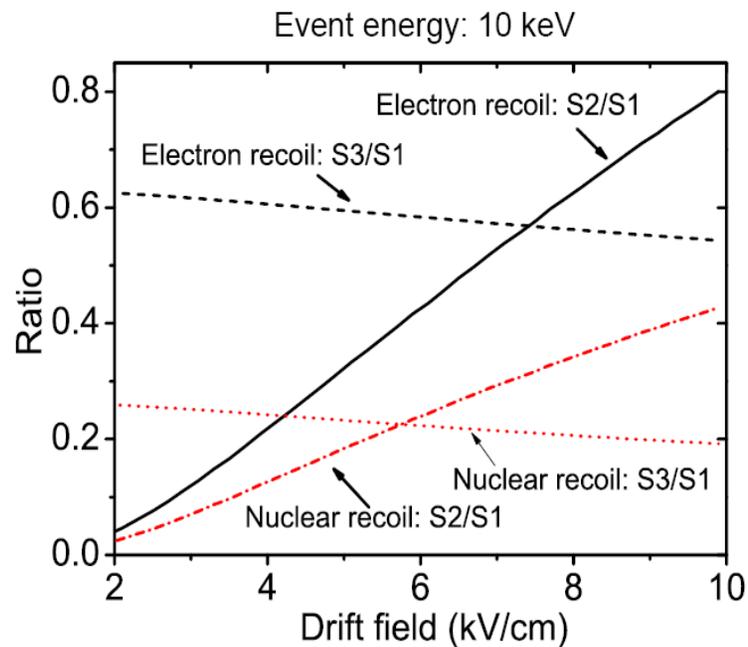
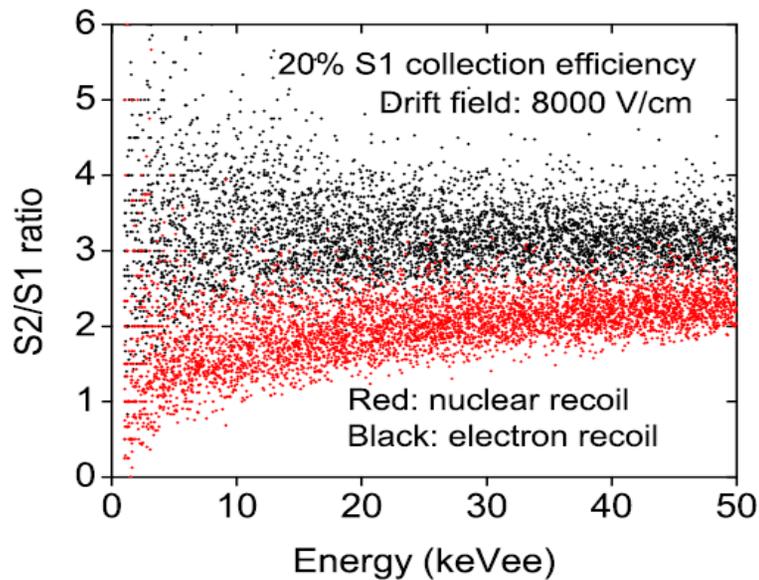
Liquid helium-4 predicted response
(Guo and McKinsey, arXiv:1302.0534,
Accepted to PRD)

Liquid helium has lower electron scintillation
yield for electron recoils (19 photons/keVee)

But, extremely high L_{eff} , good charge/light
discrimination and low nuclear mass for
excellent predicted light WIMP sensitivity



Predicted nuclear recoil discrimination and signal strengths in liquid helium



Summary

- Lots of progress on many fronts
 - Quantification of scintillation timing and yields
 - Photomultipliers
 - Wavelength shifters
 - LXe, LAr, LNe, LHe

.... And more progress to come!